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Increasing productivity in turning of hard-to-cut materials by means of modified flank faces

B. Denkena[a], B. Bergmann[a], T. Grove[a], O. Pape[a] *

[a]Institute of Production Engineering and Machine Tools, Leibniz Universität Hannover, An der Universität 2, D-30823 Garbsen, Germany

Abstract

The high thermo-mechanical tool load during cutting of hard-to-cut material leads to an increased tool wear, which affects the surface integrity and tool life adversely. An innovative approach to counter the wear is to retract the tools flank face at a certain distance from the cutting edge. The so-called flank face modification geometrically limits the tool wear and increases the available material of the tool, which can be removed by the abrasive cutting process until a certain tool life criterion is reached. However, the flank face modification weakens the mechanical stability of the cutting edge. To avoid tool breakage due to excessive mechanical stress, this paper presents a new design approach based on static finite element simulations. Finally, experimental results show an increase in tool life up to 75% compared to conventional tools with these designed modifications

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Keywords: Flank face modification; hart-to-cut materials; turning

1. Introduction

Titanium and nickel-based alloys are commonly used as construction materials where high mechanical strength and corrosion resistance at high temperatures are needed. Typical applications are turbine blades, exhaust valves, turbochargers, furnaces and valves in aerospace, automotive and chemical process industry [1]. Their high-temperature strength and low thermal conductivity classify them as hard-to-cut materials, because high thermal and mechanical loads act on the contact area between the tool and workpiece [2]. This leads to an excessive tool wear progression, low

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* Corresponding author. Tel.: +49-511-76218259; fax: +49-511-7625115.
E-mail address: pape@ifw.uni-hannover.de

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productivity and efficiency. Besides the substrate and coating, the tools micro geometry is a significant factor to increase tool life [3]. Regarding micro geometry, the flank face modification is an approach to limit the tool wear [4]. Fig. 1 (a) shows the geometry of modified tools, where the flank face is retracted at a certain distance below the cutting edge. Four parameters describe the resulting undercut: the width S_b, depth S_t, radius r and angle α. As shown in Fig.1 (b), this geometry affects the progression of flank wear by two aspects: First, the width of the undercut geometrically limits the contact area of the tools flank face and workpiece, which results in a lower increase of flank wear. Second, the depth of the undercut increases the available material of the tool, which can be removed by the abrasive cutting process until a certain width of flank wear is reached.

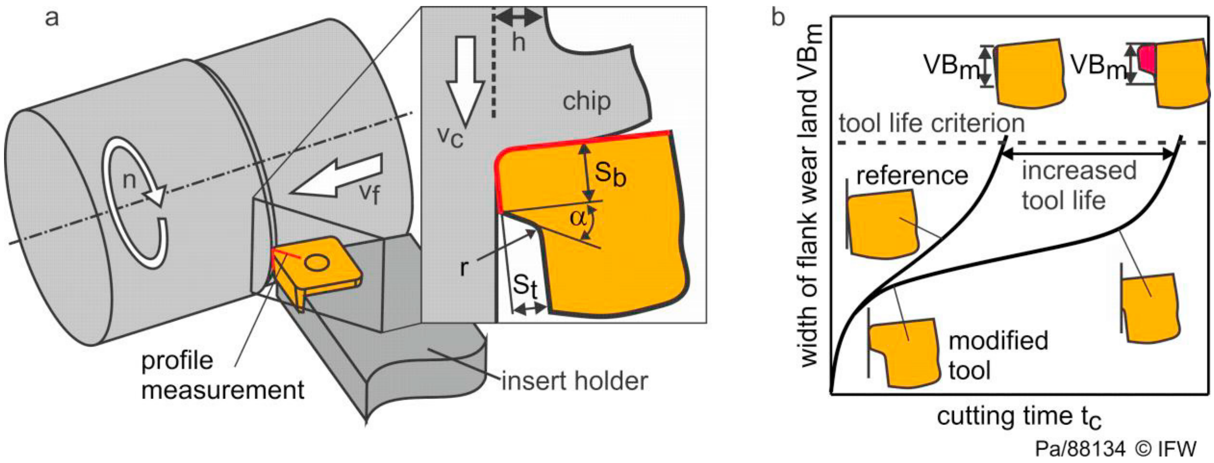

Fig. 1. (a) Geometry of modified tools; (b) effect of flank face modifications.

Within applied flank face modifications a significant increased tool life time was shown for turning (230%) and milling (100%) of hardened steel as well as for drilling of Inconel 718 (50%) [4, 5, 6, 7]. Beside tool wear, modified flank faces also positively affect the residual stress state of the workpiece surface, resulting in higher lifetimes under high cycle fatigue. Some studies also show a higher cooling lubricant volume flow up to 60% close to the cutting edge compared to conventional tools, when the coolant is supplied directly to the flank face [6, 7]. This can be explained by the greater distance between the workpiece and the flank face due to the undercut. This leads to lower thermal tool load during cutting and thus increased tool life time in drilling. However, flank face modifications increase the internal stress of the tool, so they have to be carefully designed to avoid tool breakage. Prior design methods used dynamic simulations of chip formation to calculate the inner stresses of the tool with respect to the geometry of the undercut. This simulation predicts tool breakage with an accuracy of 94.3% [5], but has two major disadvantages. First, a proper material and friction model for the investigated cutting process has to be known. Second, even with the approximation of a two-dimensional chip formation, it is time-consuming to calculate the stress state of a certain modification. These disadvantages prevent an industrial application of modified tools. Therefore, a new design approach is presented, which reduces the complexity and time consumption of the calculation.

2. Experimental setup

Experimental turning test were carried out on a Gildemeister CTX520 lathe with the PVD-coated indexable inserts CNMG120408 and CNMG120404 from Seco tools. During cutting the cooling lubricant Wisura WM 3382 was applied with high-pressure of p = 80 bar directly to the rake and flank face. As workpiece materials Ti-6Al-4V, Inconel 718, γ-titanium aluminide (Ti-43.5Al-4Nb-1Mo-0.1B) and Mar-M246 (Ni-0.15C-10Co-10W-9Cr-5.5Al-2.5Mo) were used. Table 1 shows the process parameters for each material. The different cutting speeds were chosen to reach an equal tool life of T = 10 min for conventional tools as a reference. Due to increasing notch wear when using the materials γ-titanium aluminide and Mar-M246, a higher depth of cut and smaller corner radius were chosen. Thus, the cutting edge with high notch wear does not produce the final surface, which results in a high roughness and reduced tool life. Along with flank face modifications, the clearance angle has a significant influence on wear behavior. Therefore, turning test are carried out with a clearance angle of α = 6° and α = 9°, which is adjusted by the tools cutting edge inclination. The flank face modifications are ground on a Wendt WAC715 Centro grinding machine. For wear measurement, a digital microscope Keyence VHX-600 is used

Table 1. Process parameters used for longitudinal turning test

material	cutting speed v_c	depth of cut a_p	feed f	clearance angle α	corner radius r_ε	coating
Ti-6Al-4V	200 m/min	0.3 mm	0.1 mm	6°/9°	0.8 mm	uncoated
Inconel 718	170 m/min	0.3 mm	0.1 mm	6°/9°	0.8 mm	PVD, (Ti, Al)N + TiN
γ-titanium aluminide	55 m/min	0.6 mm	0.1 mm	6°/9°	0.4 mm	PVD, (Ti, Al)N + TiN
Mar-M246	30 m/min	0.6 mm	0.1 mm	6°/9°	0.4 mm	PVD, (Ti, Al)N + TiN

Beside the investigations of the wear behavior of conventional and modified tools, process forces are measured with a three-component-dynamometer type Kistler 9121. The process forces are needed to determine the mechanical stress of modified tool during cutting.

3. Design of flank face modifications

While a higher depth S_t and a smaller width S_b of the undercut have positive effects on tool life, they also weaken the cutting edge, because the wedge of the cutting tool gets thinner. Here the process forces, which act on the contact zone between the tool and the workpiece, causes a critical compressive stress located at the radius of the undercut (Fig. 2 a). When the minimum principal stress exceeds the compressive strength of the cutting material, tool fracture occurs [5]. Figure 2 b shows the measured cutting forces, which are related to the length of the engaged cutting edge. Here, an increasing tool load leads to higher stresses and thus reduces the potential of flank face modifications for the more difficult to cut materials.

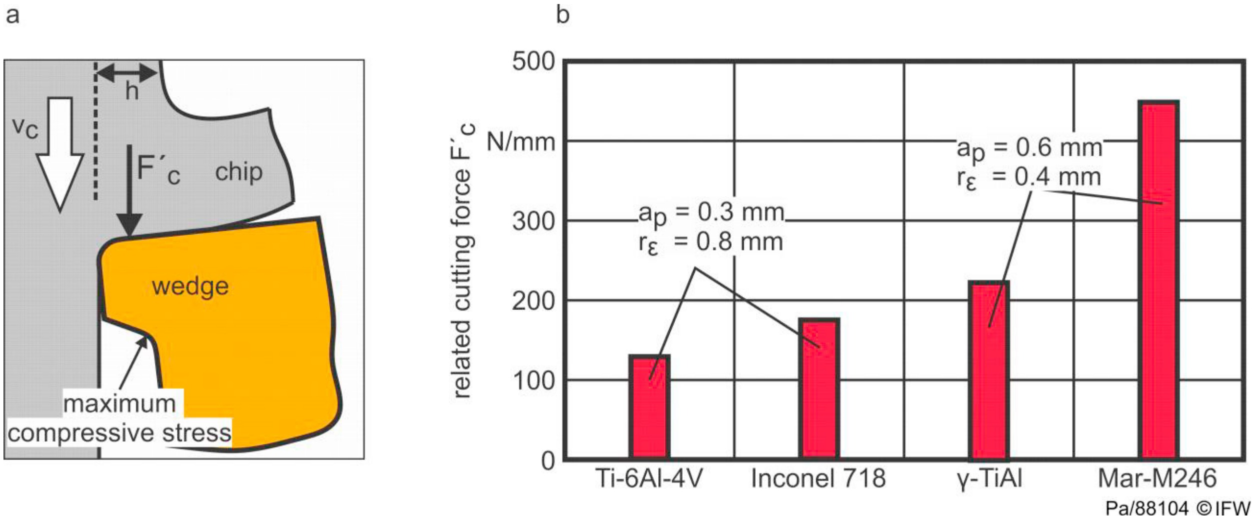

Fig. 2. (a) Maximum stress of the tool; (b) related cutting force.

The aim is to maximize the depth and minimize the width of the undercut for an optimized effect of the modification without the occurrence of tool breakage. Therefore, the exact relation between the geometric parameters of the undercut and the stress state of the tool has to be known for each material. To determine the relation, a new approach based on static finite element simulations is introduced, which mainly consists of three steps (Fig. 3). First, the cutting, feed and passive force are measured for five stepwise increased feed rates from 0.04 mm to 0.12 mm for each material in order to get the relationship between the force components and the cross-section of undeformed chip A. During the measurements, high force oscillations up to 40% of the mean value with the material Mar-M246 were observed. This can be explained with the segmented chip formation when cutting the considered materials. In contrast to a continuous chip formation, localized shear deformation and the growth of cracks from the outer surface of the chip lead to high oscillations in process forces [8].

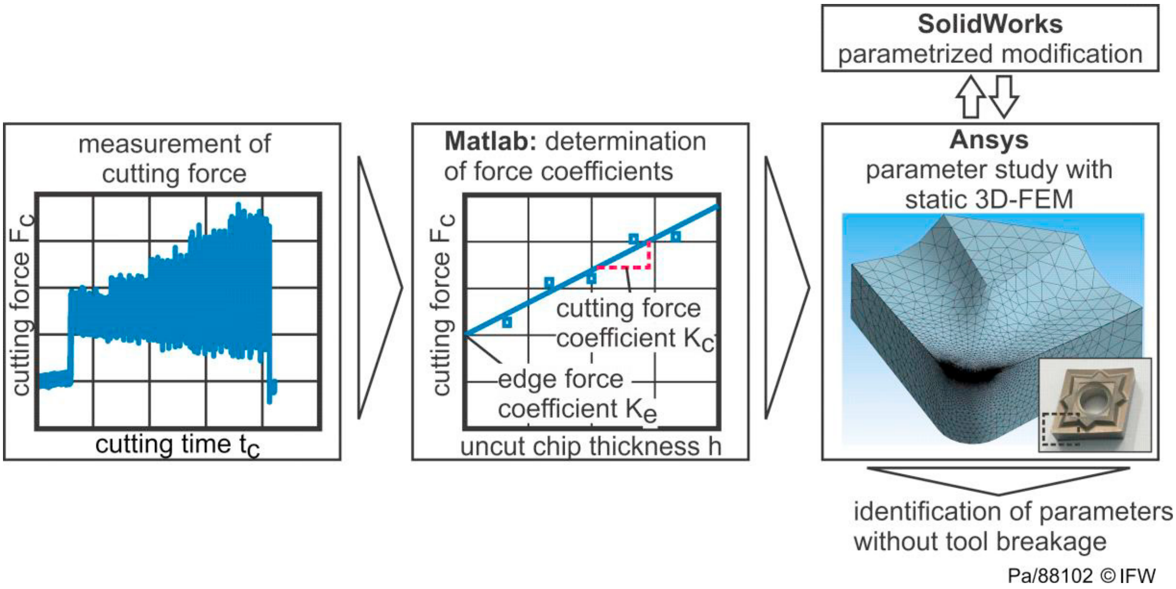

Fig. 3. Approach to design flank face modifications.

In the second step, a Matlab routine calculates the maximum force value for each feed rate. The use of maximum values instead of mean values is necessary, because they cause the critical stress state at which the tool potentially breaks. With the calculated maxima, a regression line can be fitted for each force component, which describes the maximum force value with respect to the uncut chip thickness h. According to the process force model of Altintas et al. [9], the gradient of the fitted line describes the cutting force coefficient K_{ci} while the interception of the force axis stands for the edge force coefficient K_{ei}. The cutting force coefficient can further be interpreted as a contact pressure acting on the uncut chip area projected on the rake face. In addition, the edge force coefficient represents a line contact force of the engaged cutting edge. In the third step, a static three-dimensional finite element simulation uses both coefficients as a boundary condition. Because the direction of the force components depend on the local orientation of the cutting edge, a discretization separates the contact zone into five parts (Fig. 4a). Here a maximum angular error of the stress vectors of 5° appears which is assumed as sufficient for the calculation. On each area, the cutting force coefficients act as a contact pressure in tangential, radial and axial direction to the cutting edge (Fig. 4b). Similar, the edge coefficients are applied as a line force (Fig. 4c).

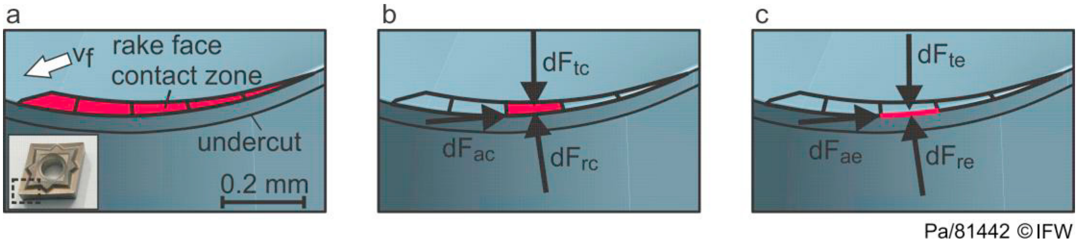

Fig. 4. : Incorporation of boundary conditions for tool load.

The software SolidWorks parameterizes the geometry of the flank face modification. With S_t and S_b as input parameters and the minimum principal stress σ_{min} in the undercut as the output parameter, the finite element software Ansys carries out a parameter study (Fig. 5a). As the mechanical properties of the tool material, a young's modulus of 650 GPa and a poission's ratio of 0.23 were set for the linear static simulation. These were provided from the tool manufacturer. With the calculated stresses at discrete values of S_t and S_b a two dimensional function of the minimum principal stress can be interpolated. Tool fracture occurs, were this function exceeds the compressive strength σ_{db} of the cutting material as a fracture criterion [5]. Therefore, the next step is to find all values of the two dimensional function were the calculated stress equals the compressive strength. Finally, the resulting curve of equal stresses has to be projected into the plane of S_t and S_b (Fig. 5b). The allowable geometric parameters are below the curve. It should be mentioned that the curve is not defined when S_b is less than 20 µm, because this leads to an invalid tool geometry.

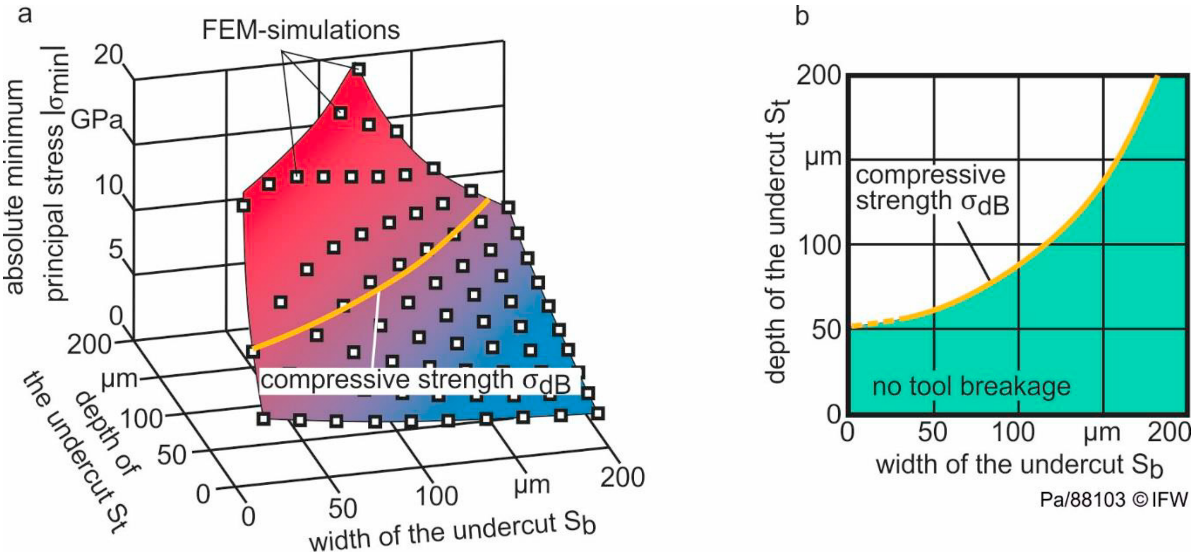

Fig. 5. : Investigation of allowable geometric parameters of flank face undercut.

Measurements of the microstructure of the investigated cemented carbide show an average grain size of 0.8 µm and a cobalt content of 5.4 wt.%. Therefore, a compressive strength of the tool material of $\sigma_{db} = 7$ GPa at room temperature was assumed according to Klünsner et al. [10]. It should be mentioned, that the compressive strength decreases due to the temperature rise during cutting. However, during the experiments, the coolant was directly applied through the tool holder to the flank face and the undercut with a pressure of $p = 80$ bar. Therefore, this effect is assumed negligible.

To validate the new design method, turning tests are carried out with various geometries of the undercut. Potential tool breakage was determined with a digital microscope after a feed travel of 10 mm. Figure 6 shows the comparison of the simulated minimum principal stress with the occurrence of tool breakage for titanium (a) and nickel-based alloys (b). For all investigated materials, the compressive strength of 7 GPa as a simulated boundary predicts tool breakage with an overall accuracy of 86%. It should be mentioned, that the calculated stresses are overestimated due to the assumed linear material behavior. To get a more accurate result, the nonlinear stress-strain curve should be taken into account, which leads to lower stresses at high strains. Nevertheless, with a sufficient safety factor, the new design method can be stated as reliable to avoid tool fracture.

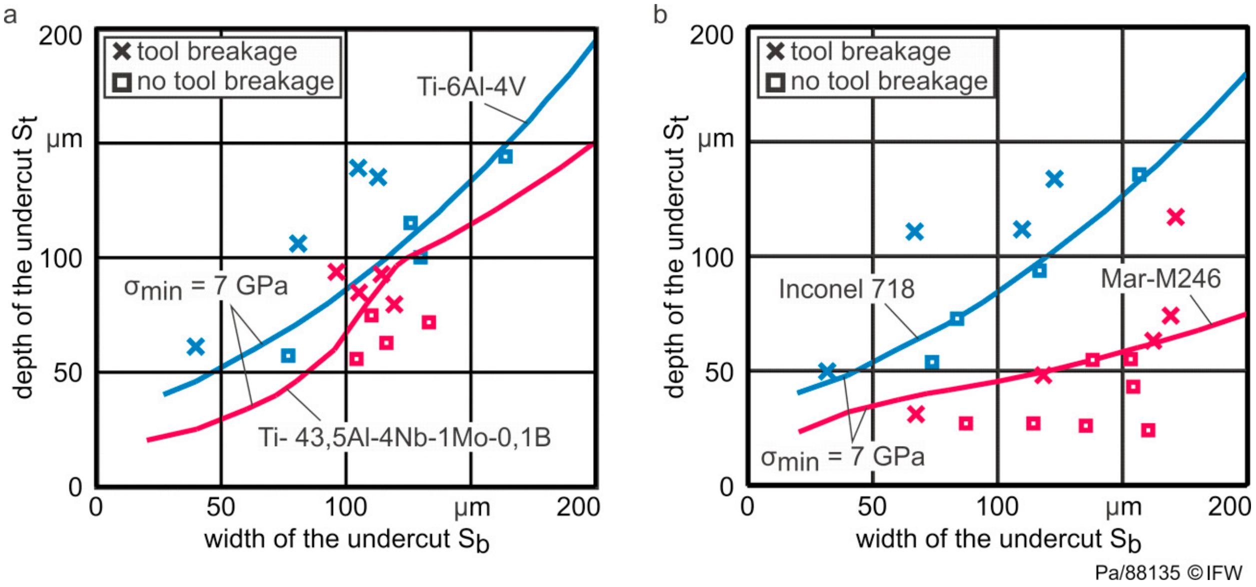

Fig. 6. : Validation of the design method for (a) titanium alloys and (b) nickel based alloys.

4. Potential of flank face modifications

Turning tests are carried out to demonstrate the potential increase of tool life with the newly design flank face modifications. The underlying tool life criterion is a maximum flank wear of 200 µm. Figure 7 shows the flank wear progression of modified tools compared to conventional tools for the material Ti-6Al-4V and γ-titanium aluminide. Using conventional tool with a clearance angle of α = 6° a tool life of 10 min was reached for both materials. By adjusting the clearance angle to α = 9°, the tool life increases by 75% when machining γ-titanium aluminide, which can be explained by a smaller contact area between the flank face and the workpiece. However, no significant increase with to a higher clearance angle was observed with Ti-6Al-4V due to cutting edge chipping. Therefore, modified tools are used with a clearance angle of α = 6° when machining Ti-6Al-4V and α = 9° for γ-titanium aluminide. Due to the undercut, an average increase of +75% of tool life can be obtained for Ti-6Al-4V. The wear behavior is mainly characterized by abrasive flank and crater wear. However, the crater wear limits a further increase of tool life, because it additionally weakens the cutting edge beside the undercut. Considering γ-titanium aluminide, the main mechanism of wear is abrasive flank wear, while no crater wear occurs contrary to the Ti-6Al-4V. For this reason, a flank face modification increases tool life by additional 75%. A further increase with a higher depth of the undercut is limited by notch wear.

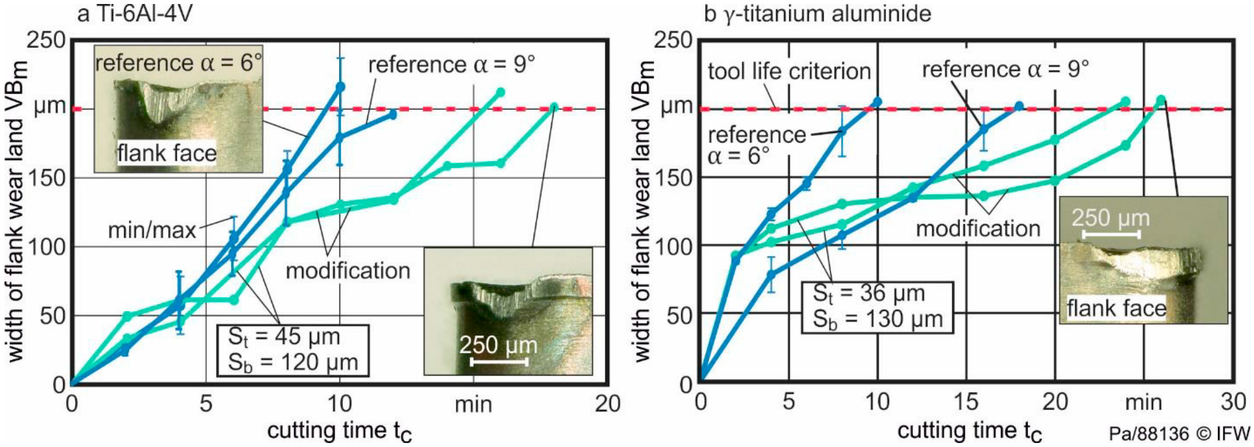

Fig. 7. : Potential of flank face modifications for (a) Ti-6Al-4V and (b) γ-titanium aluminide.

Figure 8 a shows the results for the material Inconel 718. With conventional tools, a tool life of T = 9 min was reached. A higher clearance angle increases tool life by four minutes (+ 44%). However, due to the dominant crater wear, cutting edge chipping occurs with modified tools before the tool life of the reference process is reached. This wear form weakens the cutting edge in addition to the modification and leads to higher stresses compared to conventional tools. Figure 8 b presents the results for the material Mar-M246. Similar to Inconel, notch wear limits the tool life due to the excessive mechanical stresses when utilized with the undercut. However, before the tool breakage occurs, the width of the flank wear land is smaller compared to conventional tools. Finally, it can be stated that flank face modifications increase tool life only if flank wear is the dominant wear form.

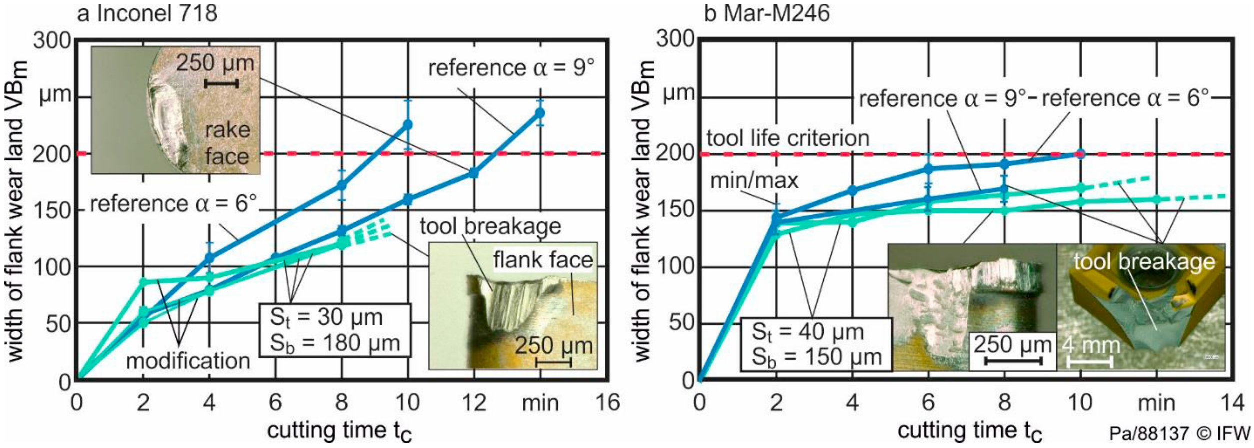

Fig. 8. : Potential of flank face modifications for (a) Inconel 718 and (b) Mar-M246.

5. Conclusion and Outlook

In this study, the design and wear behavior of flank face modifications were investigated. The design was carried out with static FEM simulations using specific force coefficients obtained from force measurements. This new approach successfully predicts tool fracture for all investigated materials with an overall accuracy of 86%. Furthermore, the design method is more practicable for an industrial application. Compared to prior methods, no complex material and friction models are needed. Only one force measurement with increasing feed rates is sufficient for the model. Moreover, the calculation time of one modification is reduced from about six hours with dynamic simulations to three minutes with the three-dimensional static simulation. This new approach can easily be applied to other workpiece and tool materials with additional force measurements.

Finally, an increased tool life, up to 75%, was achieved in experimental turning test for the materials Ti-6Al-4V and γ-titanium aluminide were the dominant wear form is flank wear. However, due to the notch and crater wear, no increase in tool life was observed for the nickel-based alloys. The results of this paper establish an approach for the development and design of flank face modifications. Further investigations on undercut geometries for milling tools and other cutting materials will be conducted.

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References

[1] G. Lütjering, J.C. Williams, Titanium, Springer, Berlin, 2007, pp. 383-408

[2] F. Klocke, A. Krämer, S. Sangermann, D. Lung, Thermo-Mechanical Tool Load during High Performance Cutting of Hard-to-Cut Materials, Procedia CIRP, 1, 2012, pp.. 295-300

[3] B. Denkena, D. Biermann, Cutting edge geometries, CIRP Annals - Manufacturing Technology 63, 2014, pp. 631 - 653

[4] R. Meyer, Neue Schneidengeometrien zur Verbesserung des Werkzeugeinsatzverhaltens beim Hartdrehen, Dr. -Ing. Dissertation Leibniz Universität Hannover, 2011

[5] B. Denkena, J. Köhler, B. Bergmann, Development of cutting edge geometries for hard milling operations, CIRP Journal of Manufacturing Science and Technology 8, 2015, pp. 43–52

[6] D. Biermann, M. Tiffe, E. Özkaya, M. Wolf, N. Beer, Simulationsbasierte Detailoptimierung von Bohr- und Gewindewerkzeugen

[7] N. Beer, Systematische Untersuchung von Vollhartmetall-Wendelbohrern zum Bearbeiten von Inconel 718, Dr. -Ing. Dissertation, Universität Dortmund, 2016

[8] S. Sun, M.Brandt, M.S.Dargusch, Characteristics of cutting forces and chip formation in machining of titanium alloys, International Journal of Machine Tools & Manufacture 49, 2009, pp. 561 - 568

[9] S. Engin, Y. Altintas, Mechanics and dynamics of general milling cutters. Part II: inserted cutters. International Journal of Machine Tools & Manufacture 41, 2001, pp. 2213–2231

[10] T. Klünsner, S. Marsoner, R. Ebner, R. Pippan, J. Glätzle, A. Püschel, Effect of microstructure on fatigue properties of WC-Co hard metals, Procedia Engineering 2, 2010, pp. 2001–2010